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Nelius

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AERODYNAMIC AND THERMAL OPERATING CHARACTERISTICS OF A 45-DEG-SLANT, SEGMENTED WALL, MAGNETOHYDRODYNAMIC GENERATOR CHANNEL UNDER NO-POWER CONDITIONS

M. A. Nelius, R. J. LeBoeuf, and J. D. McNeese

ARO, Inc.

October 1968

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FOREWORD

The test program reported herein was conducted at the request of the Air Force Aero-Propulsion Laboratory (AFAPL), Air Force Systems Command (AFSC), Wright-Patterson Air Force Base, Ohio, for Chrysler Corporation, Space Division, Huntsville Operations, under Program Element 6250901R/0617.

The results of the test were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract F40600-69-C-0001. The test was conducted from February 9 to March 28, 1968, in Propulsion Research Area (R-2C-4) of the Rocket Test Facility (RTF) under ARO Project No. RW0732, and the manuscript was submitted for publication on September 11, 1968.

Information in this report is embargoed under the Department of State International Traffic in Arms Regulations. This report may be released to foreign governments by departments or agencies of the U. S. Government subject to approval of the Air Force Aero-Propulsion Laboratory (APIE-2), or higher authority within the Department of the Air Force. Private individuals or firms require a Department of State export license.

This technical report has been reviewed and is approved.

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ABSTRACT

A test program was conducted to determine the aerodynamic and thermal operating characteristics of a 45-deg-slant, segmented wall, magnetohydrodynamic generator channel under no-power conditions. The generator channel was 30.3 in. long with an inside diameter of 2.0 in. at the inlet that diverged to 4.9 in. at the channel exit. The plasma was provided by a liquid-oxygen/JP-4 combustor with a nozzle exit Mach number of 1.76. The propellants were seeded with potassium hydroxide (KOH) dissolved in ethyl alcohol to produce a high ion concentration in the exhaust stream. Combustor operating conditions were nominally: chamber pressure, 250 to 300 psia; oxidizer-to-fuel ratio, 1.9 to 2.8; and KOH concentration, from 0 to 1.7 percent of total propellant weight flow. Firing durations ranged from 2.6 to 10.9 sec. Tabulations of combustor performance data and of the generator channel thermal and pressure data are presented.

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SECTION I
INTRODUCTION

A magnetohydrodynamic (MHD) electric power generator is classed as a direct-energy conversion device. Ionized gas flowing at high velocity through a channel is acted upon by a transverse magnetic field to produce an electromotive force (emf) perpendicular to the velocity vector and the magnetic field vector. The same physical principles are involved in an MHD generator as in a conventional electric generator except that conducting gases replace the metallic conductors of the rotor.

Chrysler Corporation, Huntsville Operations (CHO), is currently engaged in a research and development program aimed at the development of a one-megawatt, flightweight, MHD generator system to power a plasma arc illuminator. Primary components of the system will include a combustor (plasma generator) coupled to an MHD channel immersed in a magnetic field provided by a superconducting magnet. The output of the MHD generator will power the plasma arc illuminator.

As a part of the overall development program, the test program reported herein was conducted to determine the combustor and MHD channel operating characteristics under no-power conditions. Specific test objectives were to determine the channel axial pressure distribution and the variation in channel temperature with combustor burn time and to confirm that channel construction was adequate to contain the gas generated by the combustor. The program was conducted in Propulsion Research Area (R-2C-4) of the Rocket Test Facility (RTF). Design and fabrication of propellant, instrumentation, and exhaust systems were provided by RTF personnel. The channel and diffuser were provided by the Chrysler Corporation, and the combustor was provided by the Air Force Rocket Propulsion Laboratory (AFRPL).

This report presents the data obtained from 12 firings through an uncooled heat-sink-type MHD channel. A description of the combustor, channel, and associated systems is given, and the methods used to obtain the required measurements are presented.

SECTION II
APPARATUS

2.1 TEST ARTICLE

The test article consisted of a combustor and a 45-deg-slant, segmented wall, MHD generator channel and diffuser. These components are described in detail in the sections to follow.

2.1.1 MHD Generator Channel

The MHD generator channel (Fig. 1, Appendix I) is approximately 30.3 in. long with an outside diameter of 5.12 in. at the inlet, diverging to 6.10 in. at the exit. The inside diameter is 2.0 in. at the inlet and diverges to 4.9 in. at the exit. The 30.3-in.-long active portion of the channel is assembled from 103 individually insulated wall segments. Each segment is attached to adjacent segments by eight ceramic-insulated stainless steel screws.

Transition from the engine nozzle exit to the channel entrance is effected by an unsegmented electrolytic, tough pitch (ETP) copper cylinder (forward transition element) with a constant 2-in. inside diameter and 5.12-in. outside diameter. The channel segments (Fig. 2) are 0.1875-in.-thick ETP copper slabs electrically insulated from each other by a plasma-sprayed aluminum oxide (AL_2O_3) coating of 0.006-in. thickness on each mating face, separated by 0.010-in.-thick Fiberfrax 970C® paper. A layer of 0.020-in.-thick Fiberfrax 970A paper provided electrical insulation between element number 103 and the diffuser and between all segments from the aft face of segment number 26 to the diffuser. The segments are inclined forward at 45 deg to the channel axis to form a laminate array.

The channel is installed in a silicone resin-bonded glass fabric support tube (Fig. 1) to protect against bending stresses. The tube is 49.50 in. in length with a 6.38-in. inside diameter and 0.12-in. wall thickness. An insert of Marinite 36® contoured to fit the bottom quadrant of the channel and having a constant outside radius of 3.19 in. was installed between the channel and the support tube. Phenolic flanges of 8.62-in. outside diameter and 0.75-in. thickness were attached to the ends of the support tube for handling purposes.

The diffuser is a constant-area, unlaminated ETP copper duct, 24 in. in length, with an outside diameter of 6.10 in. and a wall thickness of 0.6 in.

The channel, forward transition element, diffuser, support tube, and associated instrumentation lines were delivered to the RTF as an integral unit.

2.1.2 Combustor

Ionized gas to the MHD generator channel is provided by a liquid oxygen (LO_2)/JP-4 Atlas vernier engine (Fig. 3), modified to adapt to the channel forward transition element flange. Combustor operating conditions were nominally: chamber pressure, 250 to 300 psia and oxidizer-to-fuel (O/F) ratio, 1.9 to 2.8. A seeding agent consisting of a saturated solution of potassium hydroxide (KOH) in MIL-A-6091 ethyl alcohol (21-percent KOH by weight) is injected into the JP-4 upstream of the combustor to provide exhaust gas ionization.

The combustor was cooled by circulating water through the modified regenerative fuel cooling passages. The cooling water flow rate was 3.5 lb_m/sec, with a temperature rise during firing of approximately 25°F.

1.645
1.639
1.653
1.665

The contoured supersonic nozzle section diverges from a diameter of 1.65 in. at the throat to 2 in. at the exit, providing an area ratio of 1.47 and a nominal exit Mach number of 1.76. Nozzle exit half-angle was 0 deg.

2.012

2.2 INSTALLATION

The combustor and the channel assembly were installed in Propulsion Research Area (R-2C-4). A photograph and a schematic of the installation are shown in Fig. 4. The combustor was mounted on a support stand and connected to the facility propellant and coolant systems. The forward flange of the channel was aligned with and bolted to the combustor nozzle flange. The channel diffuser extended through a rubber slip-joint seal at the forward bulkhead of a spray chamber, containing one air spray ring and six water spray rings.

The spray chamber (Fig. 5) consisted of a 36-in.-diam, 10-ft-long cylinder made of 0.25-in. mild steel, containing five cooling water spray rings. A stainless steel conical spray chamber extension 50 in. long, containing an air spray ring and a water spray ring, extended forward from the main body of the spray chamber to hold the diffuser rubber slip joint. The air spray ring was located around and just forward of the diffuser exit plane and provided a nonconducting shroud around the ionized exhaust gases to prevent electrical conduction to the spray chamber walls until the exhaust gases were cooled below the ionization temperature. The spray chamber was electrically isolated from the ground through the use of insulated support pads and water lines. A 12-in. exhaust duct was bolted to the downstream end of the spray chamber to direct the cooled exhaust gases into the facility exhaust ducting to be discharged into the atmosphere.

A schematic of the propellant system is shown in Fig. 6. Engine ignition was accomplished with a 0.5-lb_m mixture of TEAB, which consisted of 15-percent triethylaluminum (TEA) and 85-percent triethylborane

(TEB) pyrophoric fuels. The LO_2 was supplied from two 550-gal tanks pressurized with gaseous nitrogen (GN_2). An automatic pressure control system maintained tank pressure during firing at a value that provided the desired flow.

The JP-4 was supplied to an aircraft-type fuel pump from facility storage at a pressure of 60 psia. The desired engine JP-4 flow rate was provided by adjustment of a fuel bypass system back to the facility fuel storage reservoir. The pressure-fed alcohol-KOH seeding agent was injected into the JP-4 line upstream of the engine injector. All propellant systems incorporated provisions for purging the lines with dry gaseous nitrogen.

2.3 INSTRUMENTATION

Instrumentation was provided to measure combustor chamber pressure, injector pressures, propellant and seed flow rates, propellant tank pressures, combustion chamber cooling water flow rate and temperature rise, channel wall static pressures, spray chamber pressure, and channel wall temperatures. Channel pressure and temperature sensing locations are shown in Fig. 7.

Bonded strain-gage-type transducers were used to measure pressures. Propellant, seed, and cooling water flow rates were measured with turbine-type flowmeters. Iron-constantan (IC) thermocouples were used to measure fuel and seed temperatures. Copper-constantan thermocouples were used to measure liquid-oxygen temperatures and cooling water inlet and discharge temperatures. Chromel®-Alumel® (CA) thermocouples were used to measure channel wall temperature at 13 locations.

Primary combustor data were obtained from two combustion chamber pressure channels, two injector pressure channels, two fuel flow channels, two seed flow channels, and two oxygen flow channels. The propellant and seed flow signals were transmitted through wave shaping converters to a magnetic tape system where they were stored for reduction at a later time by an electronic digital computer. The computer provided a tabulation of average absolute values for each 0.1-sec time increment. The pressure and temperature data were recorded on magnetic tape from a multi-input, high-speed, analog-to-digital converter at a scan rate for each channel of 75 times/sec. A photographically recording, galvanometer-type oscillograph recording at a paper speed of 10 in./sec provided an independent backup of selected instrumentation channels.

Estimated measurement uncertainties, range of measurements, types of measuring and recording devices, and methods of system calibrations for all measured parameters are presented in Table I (Appendix II).

SECTION III
PROCEDURE

The assembled 45-deg-slant MHD channel was received at AEDC on January 8, 1968. The channel was installed, and thermal test runs were made for a variety of operating conditions and seed flow rates.

The sequence of events for each firing was accomplished automatically by use of electric timers and relays. A typical firing sequence was as follows:

t_o - 5 sec	Fire button manually actuated
t_o - 0.3 sec	LO_2 and JP-4 propellant valve electrical ignition sequencing initiated
t_o	Engine ignition; initiation of chamber pressure increase
t_o + 1 sec	Seed propellant valve electrically energized
t_o + 9 sec	Seed propellant valve deenergized
t_o + 10 sec	LO_2 and JP-4 propellant valves deenergized; nitrogen purge through propellant lines initiated.

The engine purge gases were directed through the channel and diffuser to assist in cooling the channel for the following firing. The purge continued until the firing panel was reset.

SECTION IV
RESULTS AND DISCUSSION

Twelve combustor firings were accomplished to evaluate the aerodynamic and thermal operating characteristics of a segmented-wall, heat sink MHD generator channel under no-power conditions. An LO_2/JP-4 combustor was utilized, which operated at nominal chamber pressures from

250 to 300 psia and oxidizer-to-fuel ratios from 1.9 to 2.8. Combustor burn time was varied from 2.6 to 10.9 sec. A seed solution of potassium hydroxide (KOH) saturated in ethyl alcohol was used to provide a high ion concentration in the combustor exhaust gases. The seed solution flow rate was varied from 0 to 33 percent of the JP-4 flow rate. All firings were accomplished with the channel exhausting to atmospheric pressure.

Specific test objectives were to determine the channel axial pressure distribution and the variation in channel temperature with time and to confirm that channel construction was adequate to contain the gas generated by the combustor.

The average values of combustor chamber pressure and propellant and seed flows are presented in Table II for the twelve test firings. Combustor operating characteristics and channel pressure and temperature distribution are discussed in the following sections.

4.1 COMBUSTOR OPERATING CHARACTERISTICS

The analog variation in chamber pressure, propellant flow rates, and injector pressures during a typical combustor ignition transient are presented in Fig. 8. The time from the initiation of TEAB/JP-4 flow and of LO_2 flow to the time of increase in chamber pressure (t_o) was nominally 0.13 and 0.06 sec, respectively. The lag time in initiation of seed flow was intentional to prevent admittance of seed into the MHD channel until the walls were relatively warm.

Typical variations of chamber pressure and JP-4, oxygen, and seed flows during a combustor firing are presented in Fig. 9. The maximum deviation in chamber pressure from the average during the steady-state portion of a combustor firing was 2 percent. Seed flow was discontinued approximately 0.5 sec prior to combustor shutdown to ensure removal of all seed residue from the channel walls. The combustor was operated at chamber pressures ranging from 266 to 300 psia, at total propellant weight flows ranging from 3.64 to 4.03 lb_m/sec, and at propellant mixture ratios ranging from 1.9 to 2.7. Characteristic velocity (c^*) ranged from 4927 to 5185 ft/sec for variations in O/F from 1.9 to 2.7.

4.2 CHANNEL STATIC PRESSURE DISTRIBUTION

The MHD channel was instrumented for measurement of pressure at 12 axial positions (Fig. 7). A typical channel pressure measuring system consisted of a 0.063-in.-diam pressure tap located on the channel horizontal centerline and connected through approximately 15 ft of 0.25-in.-diam tubing to a strain-gage-type transducer. The measuring system was relatively insensitive to rapid transient pressure variations because of the length of line between the pressure tap and transducer. A typical variation in combustor chamber pressure and measured channel pressure at four axial positions during a combustor firing is presented in Fig. 10. The times required for the chamber pressure transient during combustor ignition and shutdown were approximately 0.4 and 0.5 sec, respectively. The transient time for measured channel pressure to reach steady-state conditions was typically 3.5 sec during ignition and 3.0 sec during burnout.

The measured channel axial pressure distribution is presented in Fig. 11. Also shown is the theoretical distribution based on the ratio of channel-to-combustor throat area and one-dimensional, isentropic, compressible flow relationships. The measured values of channel-to-chamber pressure represent the average from all firings, taken when measured channel pressure had reached a steady-state level. Variations in chamber pressure, propellant mixture ratio, and seed flow had no apparent effect on the ratio of channel-to-chamber pressure. Except for the pressure measured 3.7 in. from the channel inlet, the channel pressure distribution trend was very similar to that predicted from simplified theoretical considerations.

4.3 CHANNEL TEMPERATURE VARIATION

The MHD channel contained 13 CA thermocouples installed in 0.063-in.-diam ports drilled on the channel horizontal centerline. The thermocouple ports were drilled to within 0.125 in. of the internal flow passage. The channel temperature rises during each of the 12 combustor firings are tabulated at 1-sec intervals in Table III.

The effect of seed flow rate on the temperature-time variation of upstream channel segment No. 1 is shown in Fig. 12. At seed flow rates of 0, 0.14, and 0.27 lb_m/sec, a temperature rise of 505, 605, and 860°F, respectively, was observed approximately 10 sec after combustor ignition. Seed flow had the effect of significantly increasing the rate at which channel temperature increased.

The channel temperature rise at 6 and 10 sec after ignition as a function of axial position is presented in Fig. 13 for firings accomplished with 0 and 0.27 lb_m/sec of seed flow. Channel temperature generally decreased with axial length; however, the temperatures during the firings with seed flow were always higher than during firings with no seed flow.

4.4 CHANNEL STRUCTURAL DURABILITY

A total of 12 firings having burn times ranging from 2.6 to 10.9 sec were accomplished through the channel with no maintenance required between firings. Total burn duration was 97.4 sec. With the exception of firing No. 14.3, no evidence of gas leakage between channel segments during a firing was observed. During firing 14.3, flame was momentarily observed emanating from both ends of the channel support tube (Fig. 4a) during the combustor shutdown. However, no evidence of channel or support tube deterioration or charring was observed during postfire inspection.

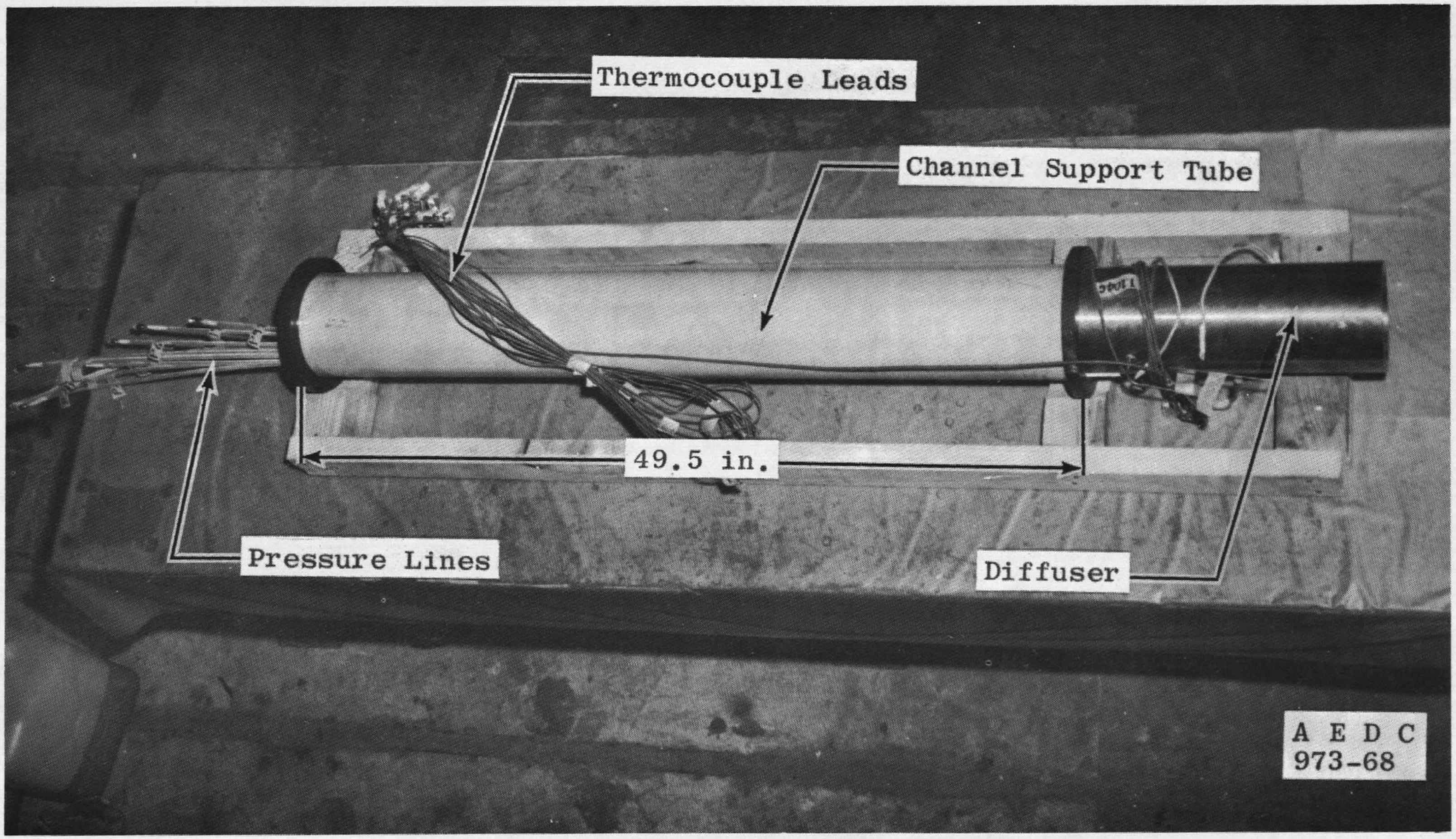
SECTION V
SUMMARY OF RESULTS

Twelve combustor firings were accomplished to evaluate the aerodynamic and thermal operating characteristics of a 45-deg-slant, segmented-wall, heat sink magnetohydrodynamic generator channel under no-power conditions. The test results are summarized as follows:

1. The combustor and channel performed satisfactorily at combustor chamber pressures ranging from 266 to 300 psia, at propellant mixture ratios ranging from 1.9 to 2.7, and for burn durations ranging from 2.6 to 10.9 sec.
2. The ratio of measured channel-to-chamber pressure was not dependent on chamber pressure, propellant mixture ratio, or seed flow rate. The channel axial pressure distribution can be approximated by one-dimensional, isentropic, compressible flow relationships.
3. An upstream channel segment temperature rise of 505, 605, and 860°F was observed approximately 10 sec after combustor ignition for firings accomplished with 0, 0.14, and 0.27 lb_m/sec of seed flow, respectively. Seed flow had the effect of significantly increasing the rate at which channel temperature increased.
4. Channel temperature generally decreased with channel length; however, the temperature during firings with seed flow was always higher than during firings with no seed flow.
5. Total burn duration accumulated during the 12 combustor firings was 97.4 sec. No evidence of gas leakage from between channel segments was observed during any firing except the last. During the final firing, flame was momentarily observed emanating from both ends of the channel support tube during combustor shutdown.

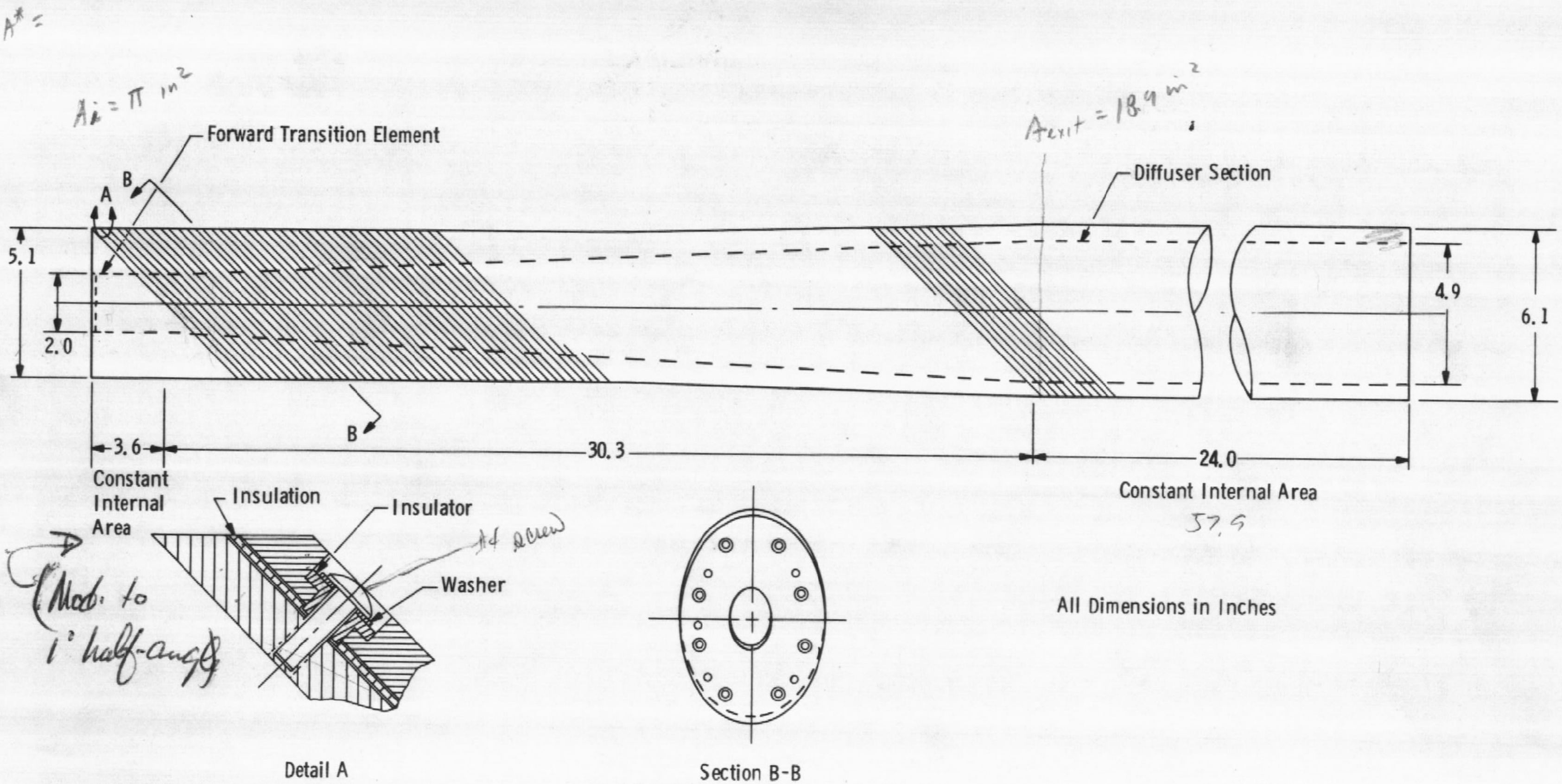
APPENDIXES

I. ILLUSTRATIONS
II. TABLES



a. Photograph

Fig. 1 MHD Generator Channel



b. Schematic

Fig. 1 Concluded

32.3

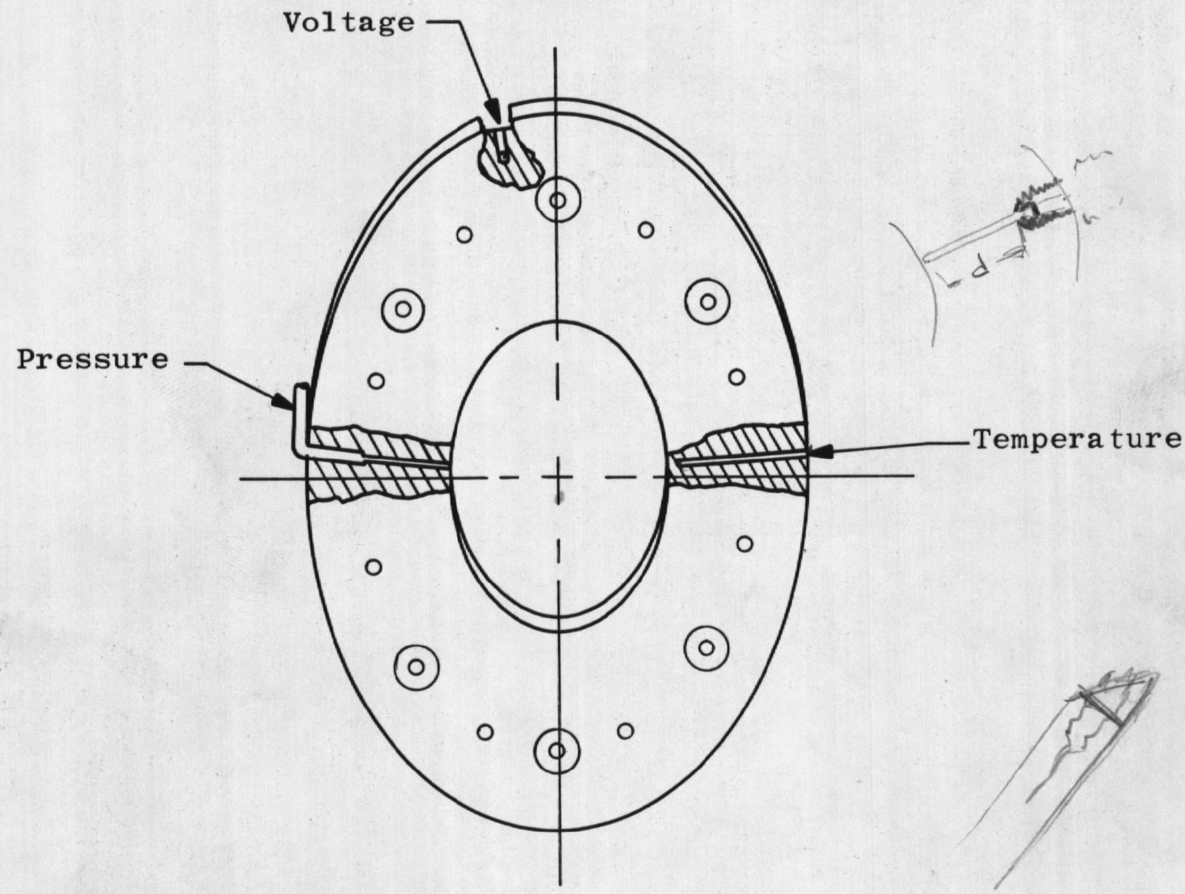
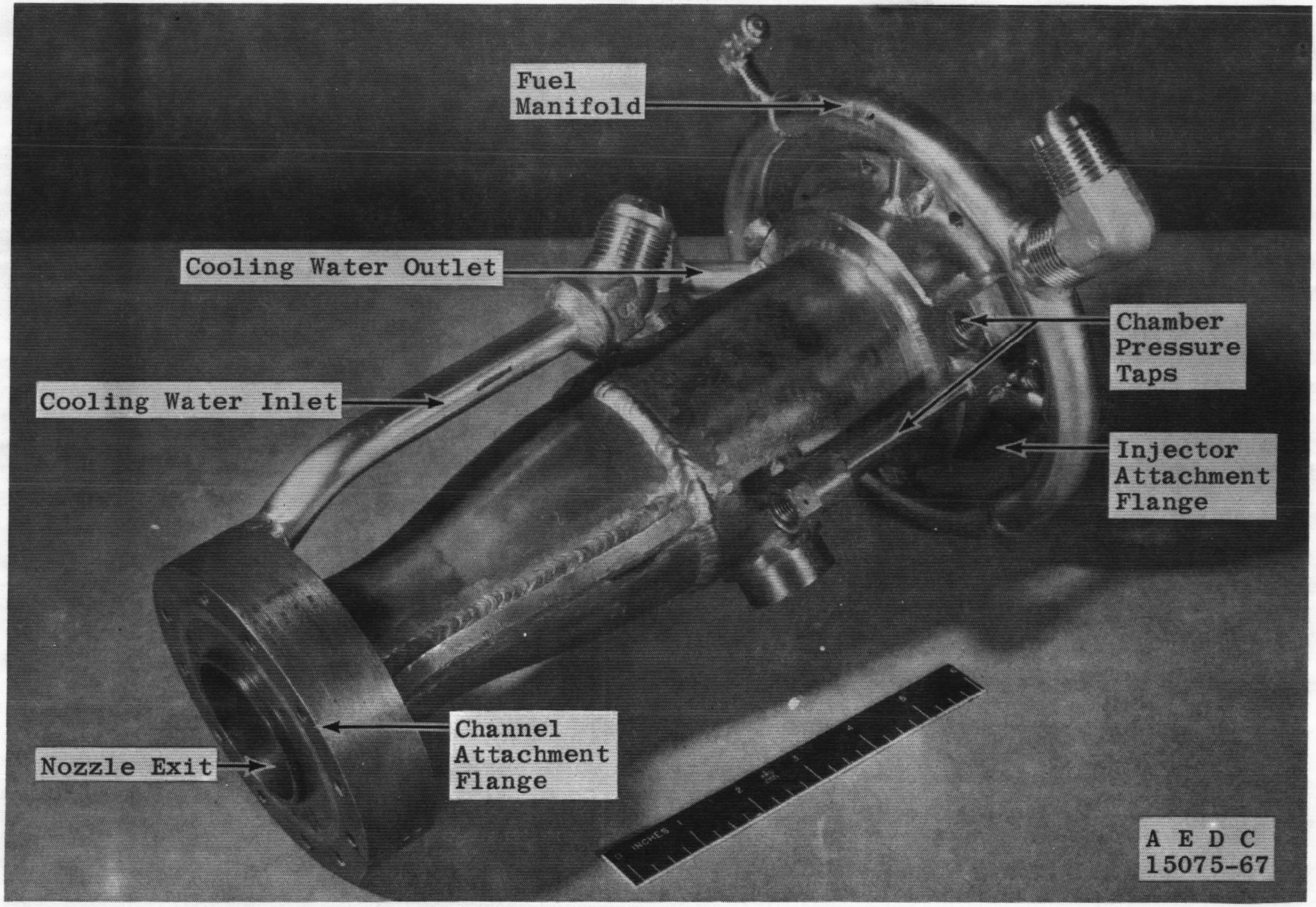
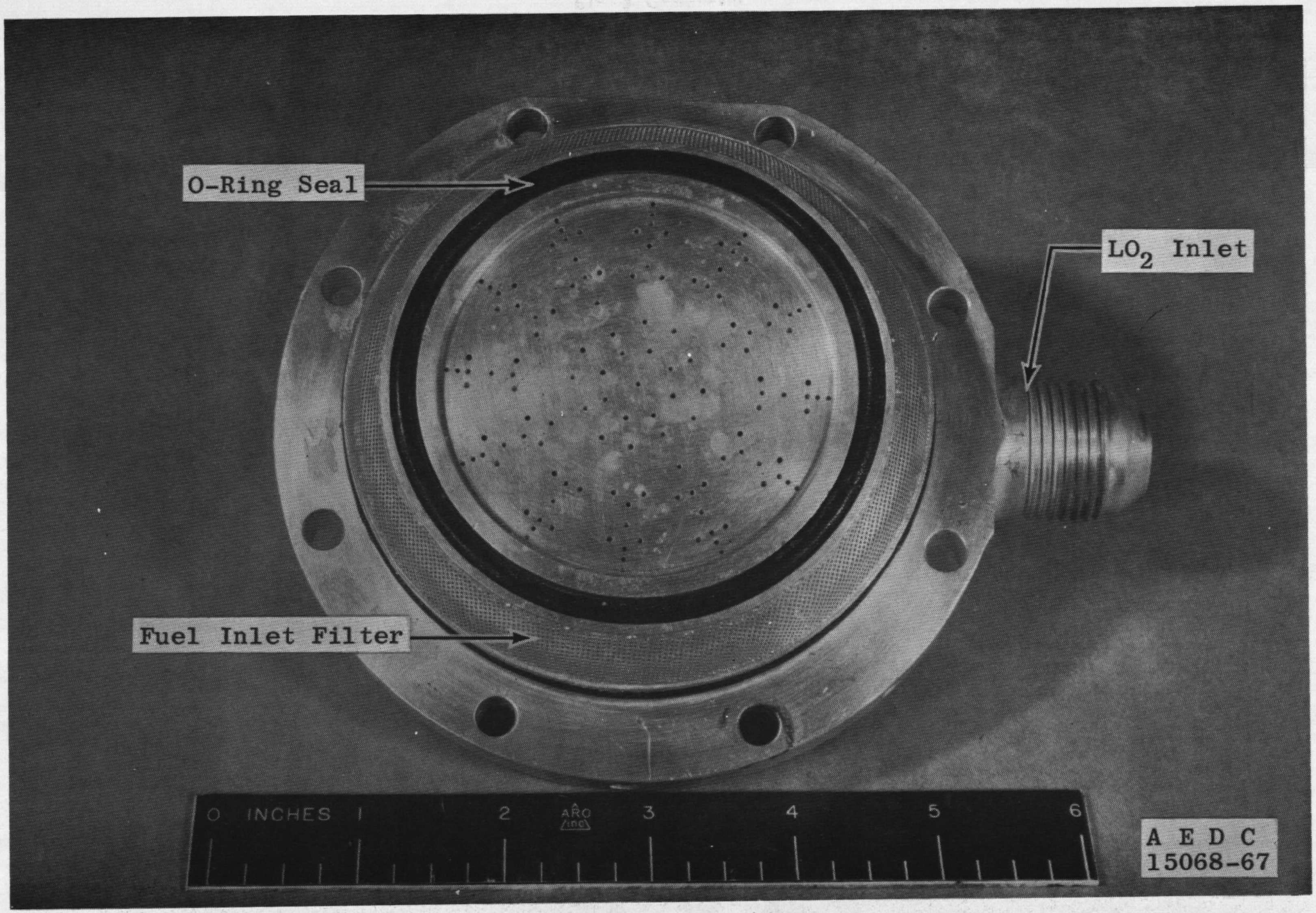


Fig. 2 Schematic of Channel Segment Showing Details of Instrumentation

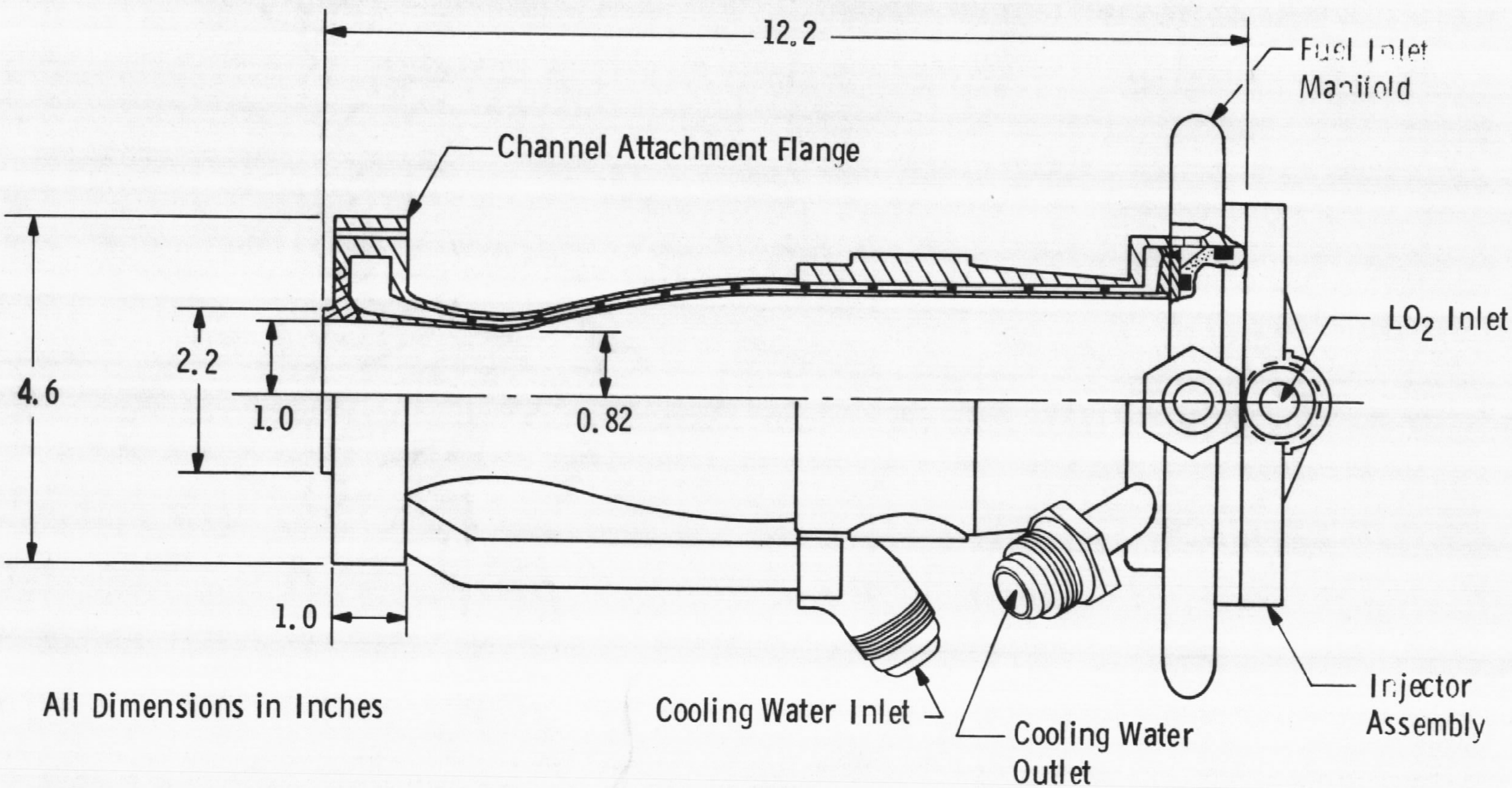


a. Photograph

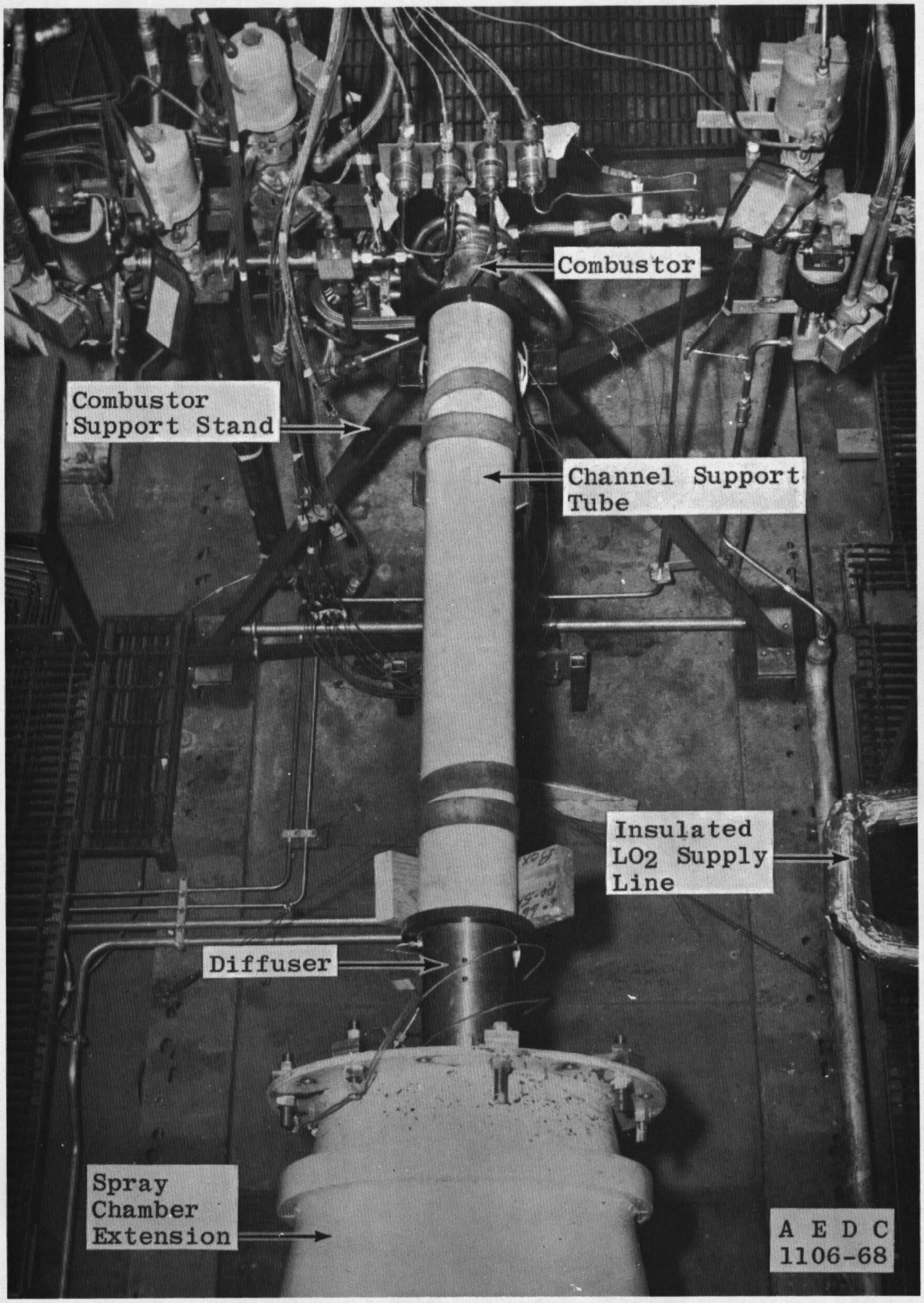
Fig. 3 Combustor



b. Injector Detail
Fig. 3 Continued

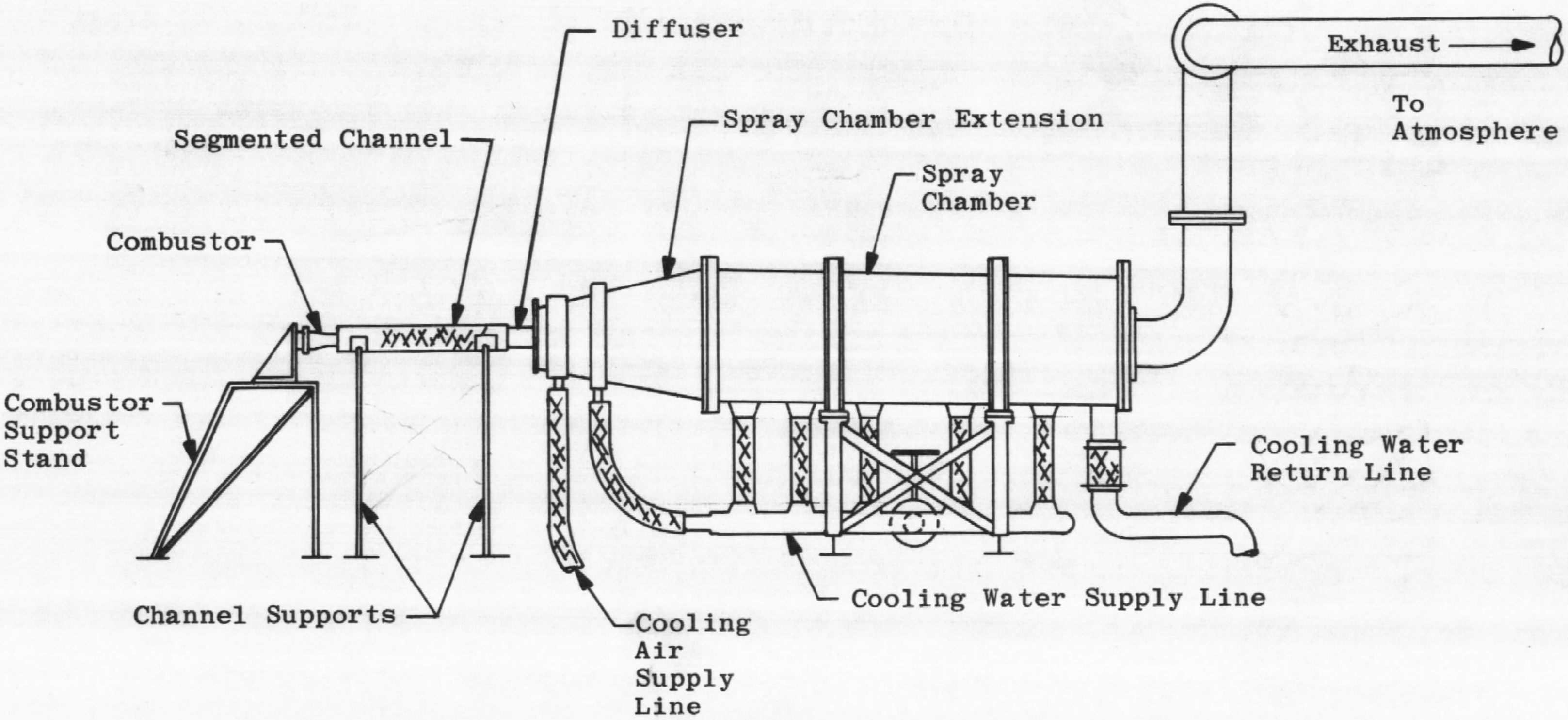


c. Schematic
Fig. 3 Concluded



a. Photograph

Fig. 4 Installation of MHD Generator Assembly in Propulsion Research Area (R-2C-4)



b. Schematic

Fig. 4 Concluded

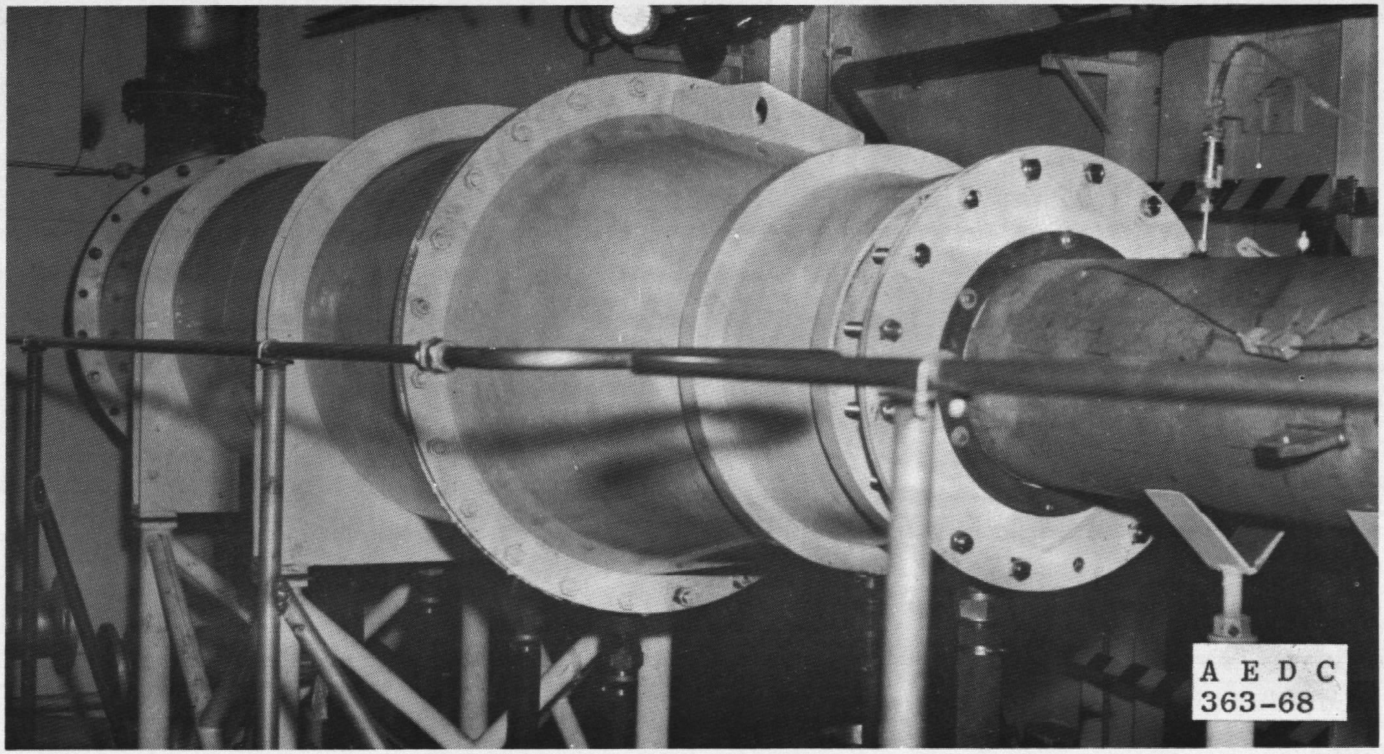


Fig. 5 Photograph of Spray Chamber

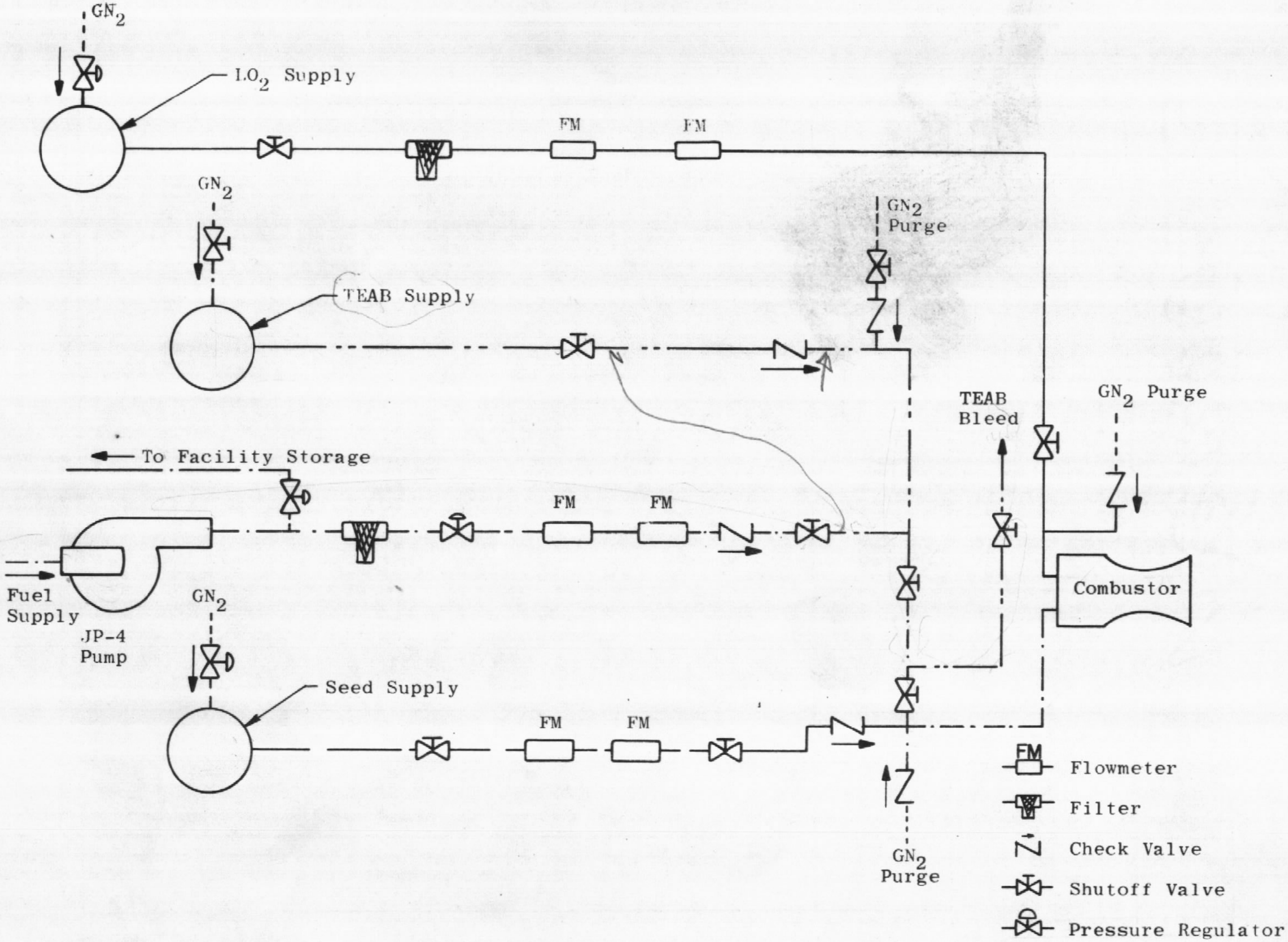
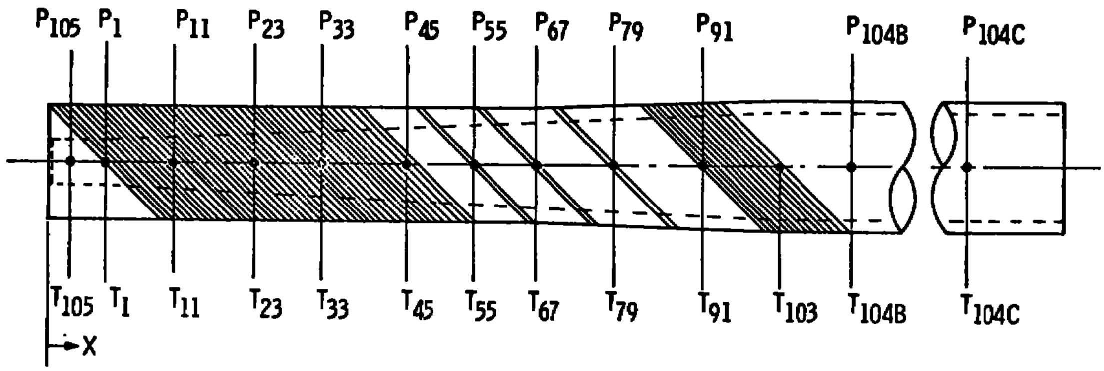


Fig. 6 Schematic of Propellant System



Element No.	Distance from Channel Inlet, X, in.	Parameter Measured: P - Pressure T - Temperature
105	1.1	P_{105}, T_{105}
1	3.7	P_1, T_1
11	6.7	P_{11}, T_{11}
23	10.2	P_{23}, T_{23}
33	13.2	P_{33}, T_{33}
45	16.7	P_{45}, T_{45}
55	19.6	P_{55}, T_{55}
67	23.2	P_{67}, T_{67}
79	26.7	P_{79}, T_{79}
91	30.2	P_{91}, T_{91}
103	33.7	-, T_{103}
104B	39.2	P_{104B}, T_{104B}
104C	52.6	P_{104C}, T_{104C}

Fig. 7 Location of Channel Pressure and Temperature Measuring Ports

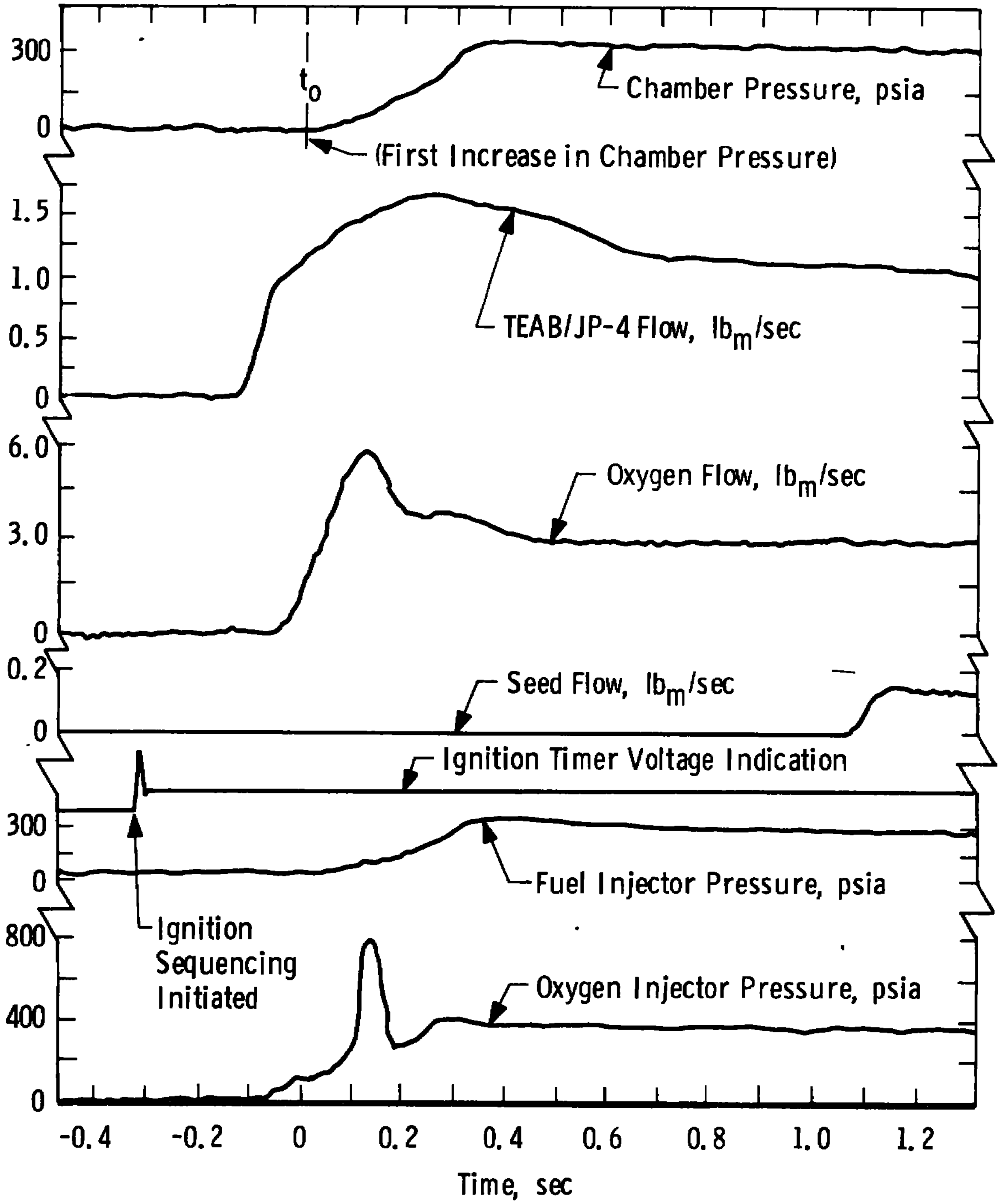


Fig. 8 Typical Engine Ignition Transient

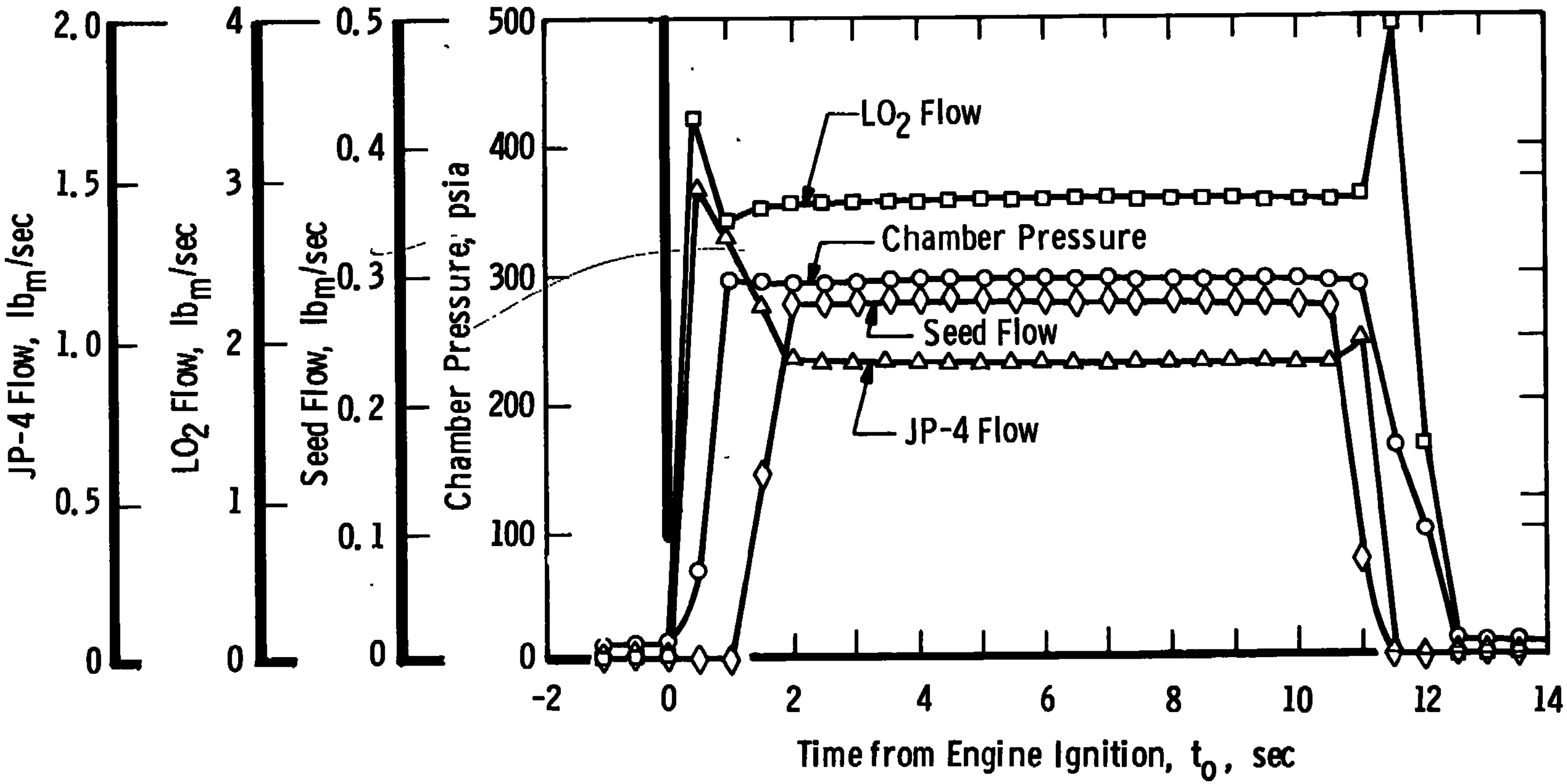


Fig. 9 Typical Variation of Chamber Pressure and of TEAB/JP-4, Oxygen, and Seed Flows during a Firing

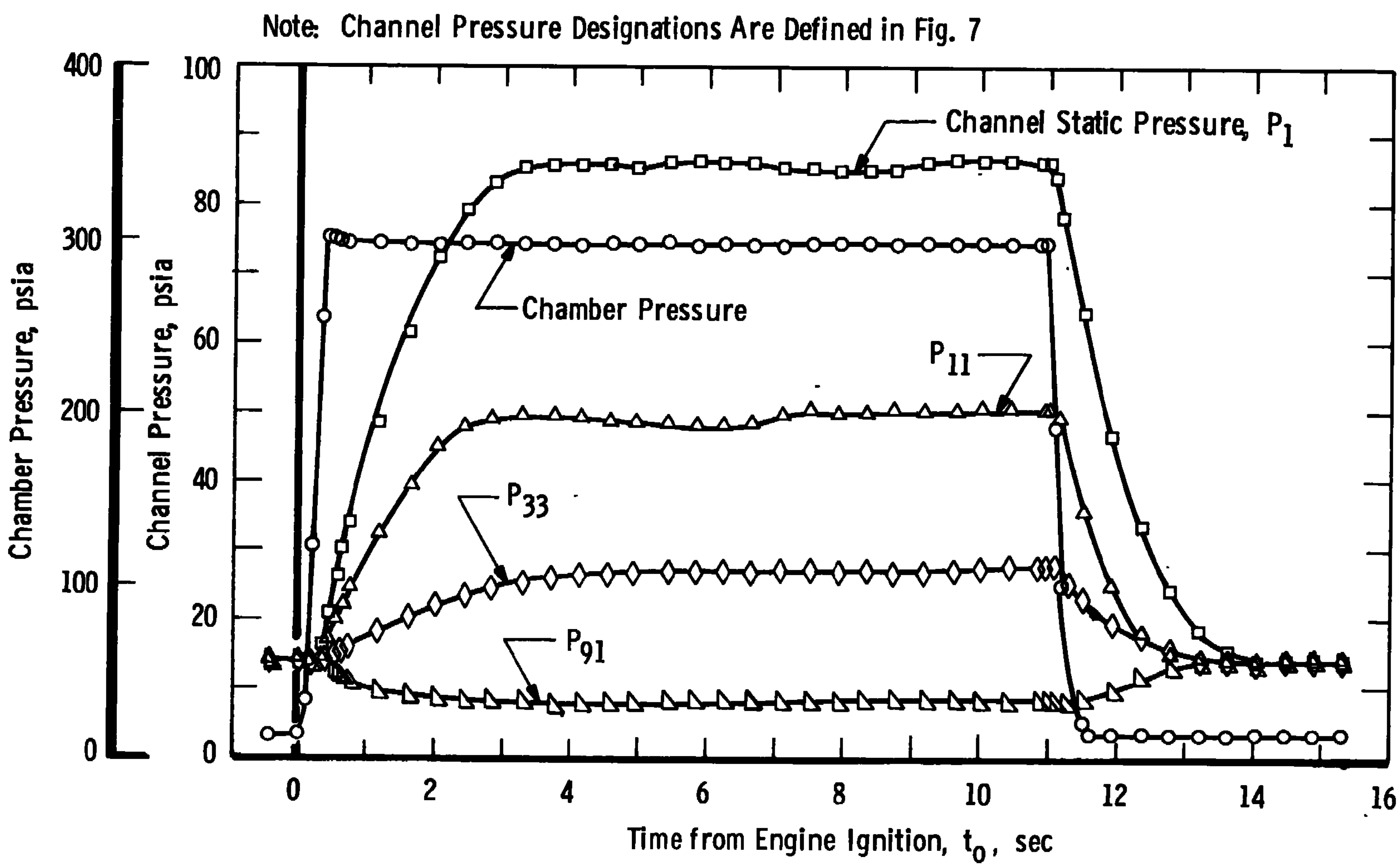


Fig. 10 Typical Variation in Channel Pressure at Four Axial Locations during Engine Firing

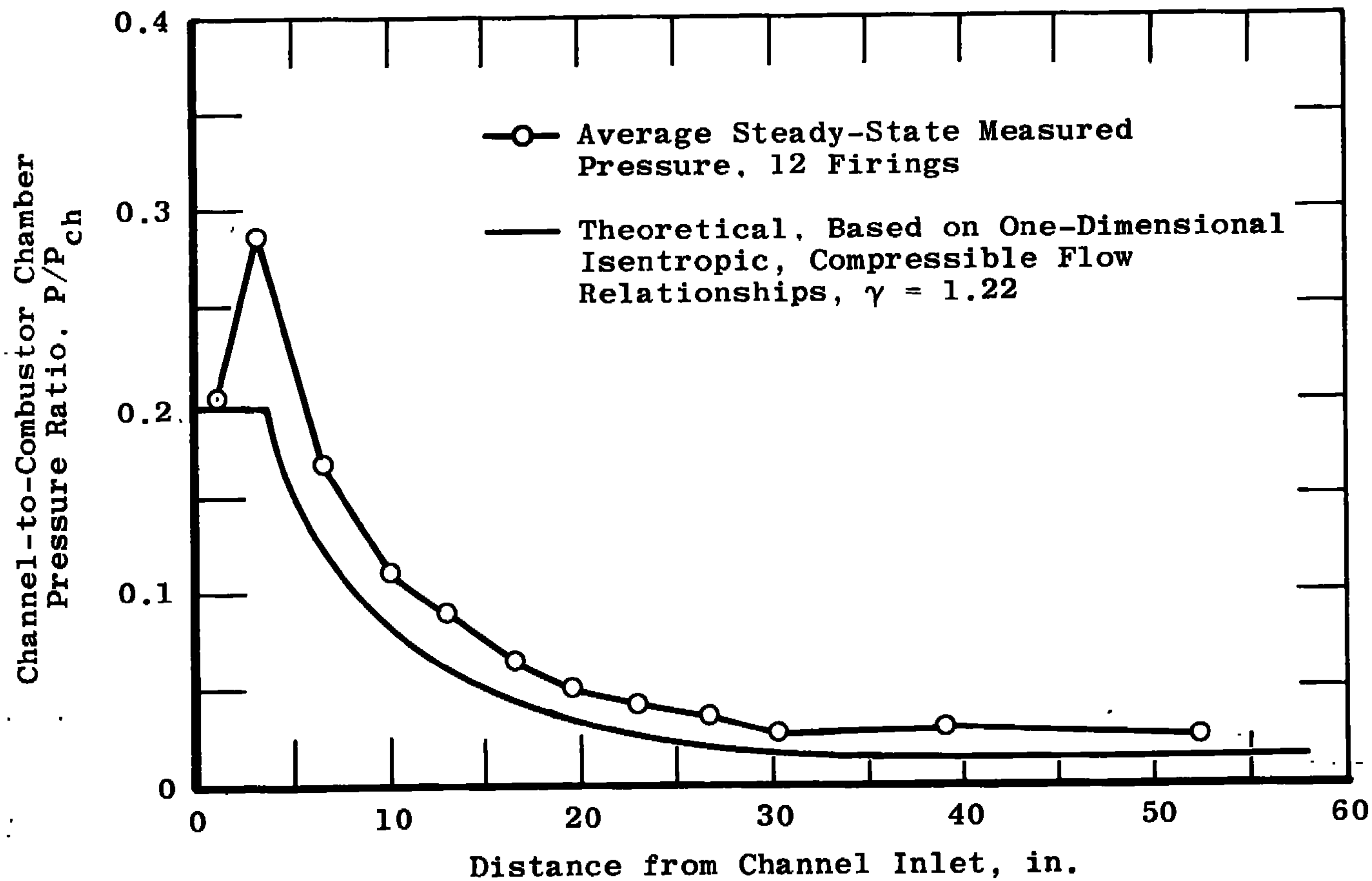


Fig. 11 Channel Axial Pressure Profile during Engine Firing

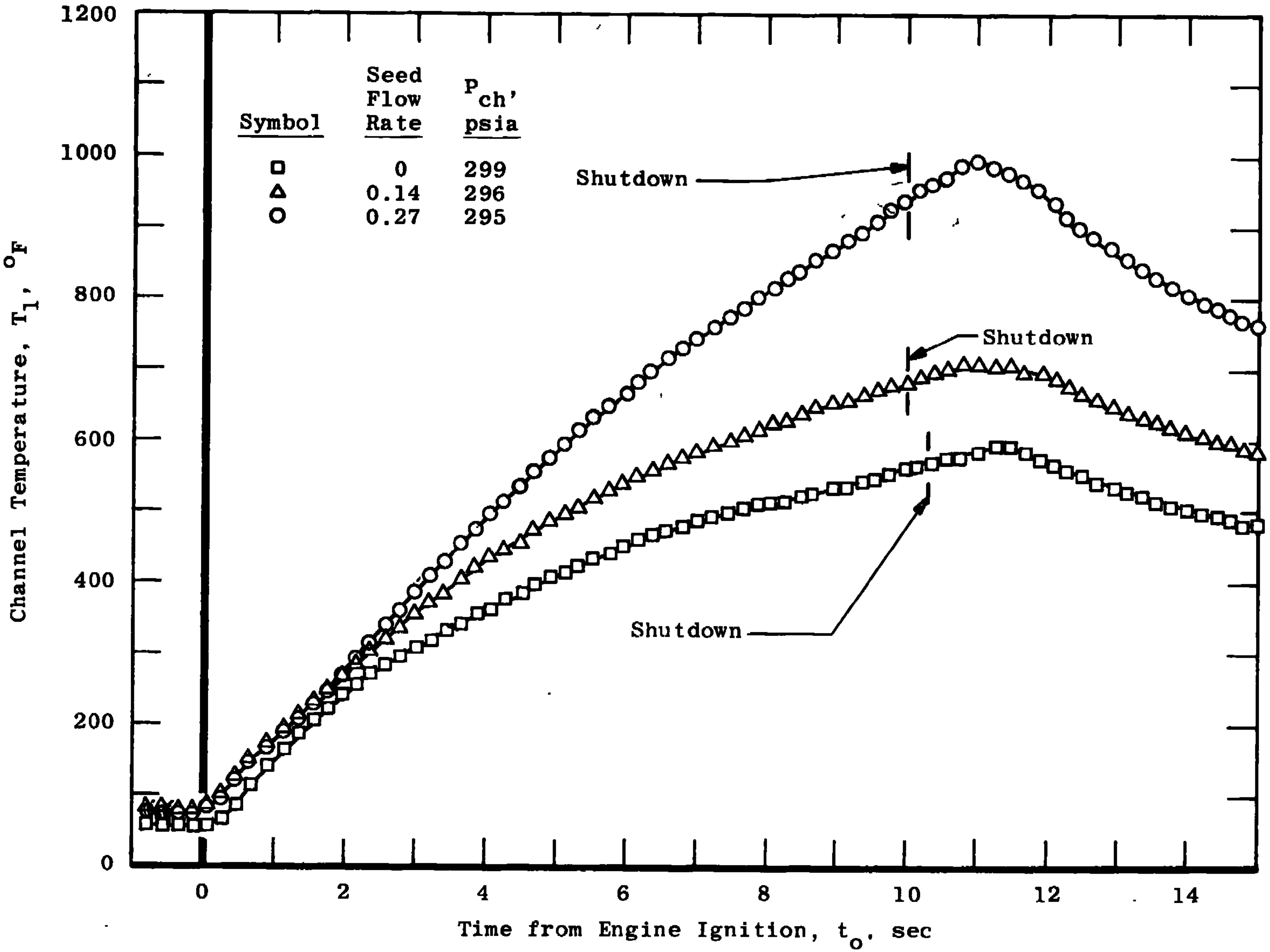
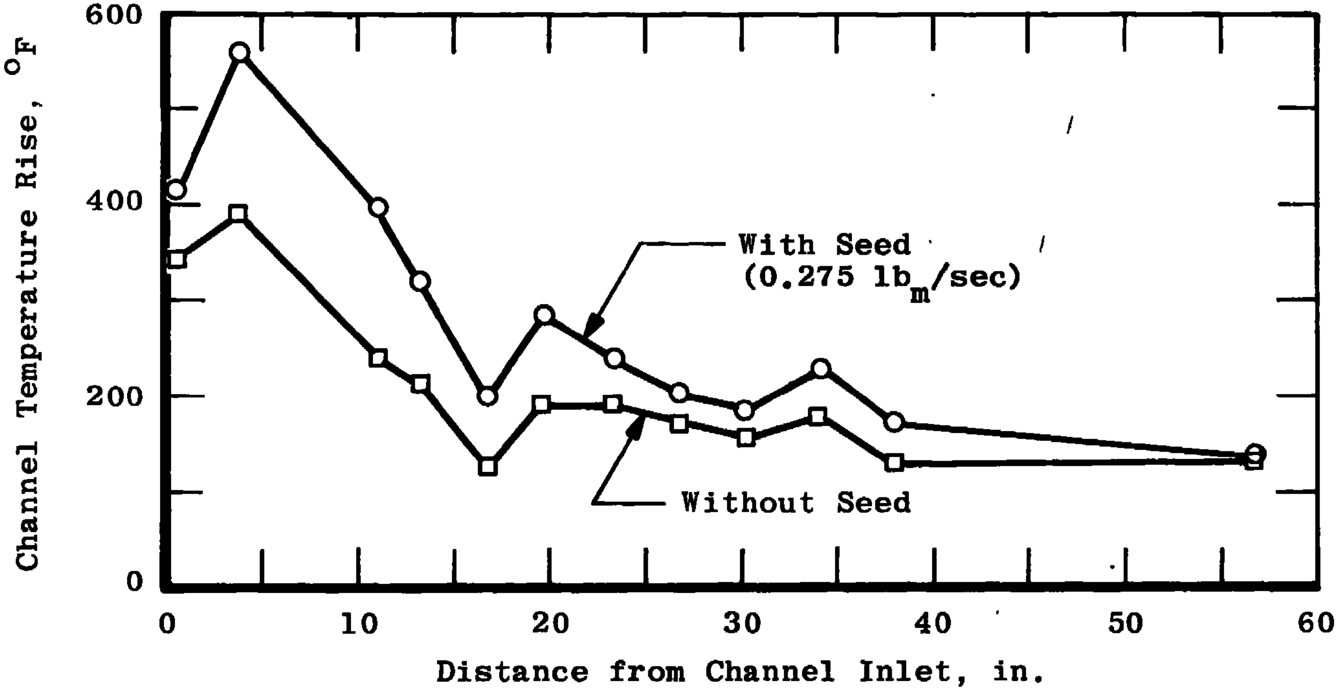
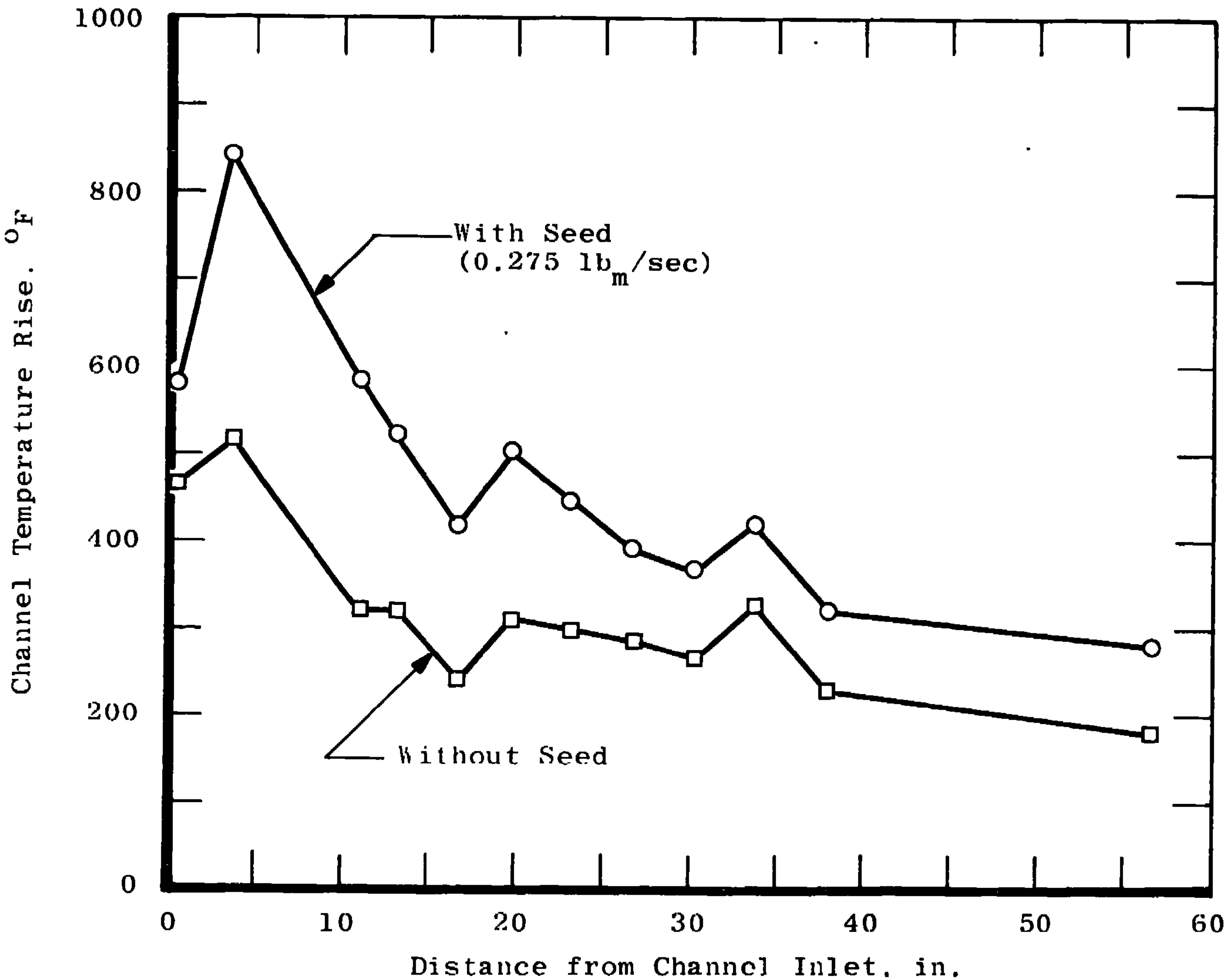


Fig. 12 Effect of Seed Flow Rate on Upstream Channel Segment Temperature as a Function of Time



a. Six Seconds after Ignition

Fig. 13 Channel Temperature Rise as a Function of Axial Position



b. Ten Seconds after Ignition

Fig. 13 Concluded

TABLE I
INSTRUMENTATION

Parameter Designation	Estimated Measurement Uncertainty (2 Sigma) — Steady-State: Percent of Reading	Steady-State: Units of Measurement	Range of Measurement	Type of Measuring Device	Recording Device: Type	Recording Device: Tape Channel Numbers	Method of System Calibration
Chamber Pressure, psia	---	±1.5 psi	200 to 300	Bonded Strain-Gage Pressure Transducer	Millivolt-to-Digital Converter, Sequential Sampling, and Magnetic Tape Data Acquisition Storage System	8, 9	Resistance Shunt
Injector Pressure, psia	---	±2.0 psi	300 to 425			24, 31	
Channel Static Pressure, psia	---	±0.125 psi	5 to 25			10 through 21	
	±0.5	---	25 to 100				
JP4 Flow Rate, lb_m/sec	±0.78	---	1.0 to 1.25	Volumetric Turbine Flow Transducer	Frequency-to-Analog Converter onto Magnetic Tape	5, 6	Frequency Substitution
Oxygen Flow Rate, lb_m/sec	±3.45	---	2.5 to 3.0			3, 4	
Seed Flow Rate, lb_m/sec	±1.57	---	0.1 to 0.3			7, 8	
Channel Temperature, °F	---	±6.3°F	0 to 1000	Chromel-Alumel Temperature Transducer	Millivolt-to-Digital Converter, Sequential Sampling, and Magnetic Tape Data Acquisition Storage System	49 through 62	Millivolt Substitution and National Bureau of Standards Temperature Tables

TABLE II
SUMMARY OF COMBUSTOR PERFORMANCE

Data Point	Combustor Chamber Pressure, psia	LO_2 Flow Rate, lb_m/sec	JP-4 Flow Rate, lb_m/sec	Seed Flow Rate, lb_m/sec	Total Flow Rate, lb_m/sec	O/F	Characteristic Velocity, c*, ft/sec	Burn/Time, sec
5.1	266	2.44	1.27	0	3.71	1.92	4927	2.6
6.3	282	2.71	1.09	0	3.80	2.49	5100	5.5
7.1	300	2.93	1.10	0	4.03	2.66	5116	5.6
7.2	299	2.88	1.08	0	3.96	2.67	5189	7.9
8.1	298	2.89	1.06	0	3.95	2.73	5185	10.9
13.1	268	2.49	0.912	0.302	3.64	2.16	5060	5.8
13.2	294	2.86	0.888	0.274	3.97	2.58	5089	5.8
13.3	295	2.88	0.878	0.275	3.98	2.62	5094	10.4
13.5	295	2.89	1.12	0	4.01	2.58	5056	10.6
14.1	299	2.89	1.11	0	4.00	2.60	5137	10.9
14.2	296	2.83	1.03	0.136	3.97	2.49	5124	10.7
14.3	295	2.85	0.908	0.274	3.98	2.53	5094	10.7

TABLE III
CHANNEL TEMPERATURE DATA SUMMARY

Parameter*	Firing Number	Initial Temperature, T_i, (°F) at Time t_o	Temperature Rise from T_i, °F										
			t_o + 1 sec	t_o + 2 sec	t_o + 3 sec	t_o + 4 sec	t_o + 5 sec	t_o + 6 sec	t_o + 7 sec	t_o + 8 sec	t_o + 9 sec	t_o + 10 sec	t_o + 11 sec
T-105	5.1	53	34	116	179	---	---	---	---	---	---	---	---
	6.3	53	46	135	197	256	297	334	---	---	---	---	---
	7.1	49	38	126	185	244	284	321	---	---	---	---	---
	7.2	49	47	126	182	236	276	312	343	377	---	---	---
	8.1	56	46	126	176	228	269	309	340	373	403	437	469
	13.1	50	108	227	264	311	347	396	---	---	---	---	---
	13.2	71	97	190	262	324	362	409	---	---	---	---	---
	13.3	91	101	191	274	329	373	419	464	505	547	588	---
	13.5	58	87	174	222	259	288	321	347	374	402	430	456
	14.1	56	143	209	250	295	328	366	401	441	469	494	517
	14.2	66	133	218	304	350	375	402	426	451	472	494	520
	14.3	62	115	208	271	331	375	421	458	495	527	565	603
T-1	5.1	53	35	116	184	---	---	---	---	---	---	---	---
	6.3	56	37	118	166	207	240	274	---	---	---	---	---
	7.1	---	---	---	---	---	---	---	---	---	---	---	---
	7.2	---	---	---	---	---	---	---	---	---	---	---	---
	8.1	59	39	122	168	206	235	266	292	322	349	385	432
	13.1	49	57	140	220	308	380	453	---	---	---	---	---
	13.2	75	54	155	252	368	456	539	---	---	---	---	---
	13.3	101	47	151	255	370	460	549	624	699	762	827	---
	13.5	60	51	160	229	298	350	400	436	471	495	523	547
	14.1	54	61	171	236	295	344	389	421	451	474	501	522
	14.2	87	74	169	242	323	384	441	484	524	556	588	615
	14.3	80	100	200	306	417	506	595	665	735	796	864	915
T-11	5.1	62	54	132	179	---	---	---	---	---	---	---	---
	6.3	65	49	134	174	202	223	245	---	---	---	---	---
	7.1	60	57	139	178	205	233	263	---	---	---	---	---
	7.2	103	55	129	168	197	217	252	284	314	---	---	---
	8.1	---	---	---	---	---	---	---	---	---	---	---	---
	13.1	---	---	---	---	---	---	---	---	---	---	---	---
	13.2	---	---	---	---	---	---	---	---	---	---	---	---
	13.3	---	---	---	---	---	---	---	---	---	---	---	---
	13.5	---	---	---	---	---	---	---	---	---	---	---	---
	14.1	---	---	---	---	---	---	---	---	---	---	---	---
	14.2	---	---	---	---	---	---	---	---	---	---	---	---
	14.3	---	---	---	---	---	---	---	---	---	---	---	---
T-23	5.1	63	45	107	138	---	---	---	---	---	---	---	---
	6.3	66	52	114	141	162	179	202	---	---	---	---	---
	7.1	63	57	118	146	168	189	223	---	---	---	---	---
	7.2	111	51	111	140	162	180	207	245	273	---	---	---
	8.1	71	58	119	147	168	186	214	244	277	302	339	361
	13.1	46	93	189	259	306	340	383	---	---	---	---	---
	13.2	102	76	167	242	305	352	402	---	---	---	---	---
	13.3	159	55	143	211	279	333	387	435	486	529	576	---
	13.5	85	53	141	167	186	202	223	244	264	282	303	321
	14.1	50	75	160	190	209	230	258	279	303	320	340	361
	14.2	172	73	152	195	245	290	336	375	418	456	498	535
	14.3	194	95	166	229	297	350	406	455	505	549	600	637
T-33	5.1	61	34	84	109	---	---	---	---	---	---	---	---
	6.3	---	---	---	---	---	---	---	---	---	---	---	---
	7.1	62	49	105	130	155	189	220	---	---	---	---	---
	7.2	113	50	100	124	148	171	209	245	276	---	---	---
	8.1	70	48	102	126	151	175	204	234	270	302	340	368
	13.1	46	45	106	161	215	259	304	---	---	---	---	---
	13.2	108	42	106	163	222	269	320	---	---	---	---	---
	13.3	162	32	89	143	199	248	303	352	406	452	502	---
	13.5	85	28	83	111	136	157	190	227	255	283	314	338
	14.1	50	49	111	139	162	188	220	247	276	298	330	362
	14.2	175	49	107	152	209	260	311	353	396	434	474	508
	14.3	196	61	119	175	232	281	337	386	438	484	536	572
T-45	5.1	61	25	70	95	---	---	---	---	---	---	---	---
	6.3	65	28	72	98	124	149	180	---	---	---	---	---
	7.1	60	30	80	108	136	173	211	---	---	---	---	---
	7.2	110	33	83	112	139	162	193	222	249	---	---	---
	8.1	69	34	89	117	144	166	206	239	273	297	324	346
	13.1	46	14	50	94	149	200	250	---	---	---	---	---
	13.2	103	6	25	50	87	126	175	---	---	---	---	---
	13.3	156	4	20	42	75	112	159	204	256	303	354	---
	13.5	81	3	17	33	53	73	96	120	148	172	201	228
	14.1	50	8	33	58	88	116	149	178	213	245	280	310
	14.2	172	14	51	86	133	181	233	279	325	363	401	433
	14.3	186	17	48	89	145	199	259	312	365	411	465	499
T-55	5.1	59	27	83	119	---	---	---	---	---	---	---	---
	6.3	63	37	96	131	165	191	221	---	---	---	---	---
	7.1	59	43	101	136	170	216	264	---	---	---	---	---
	7.2	107	40	98	133	167	195	224	261	297	---	---	---
	8.1	67	44	106	140	173	199	249	289	321	344	369	389
	13.1	46	17	52	95	149	199	256	---	---	---	---	---

*Thermocouple locations shown in Fig. 7.

TABLE III (Continued)

Parameter*	Firing Number	Initial Temperature, T_i, (°F) at Time t_o	Temperature Rise from T_i, °F										
			t_o + 1 sec	t_o + 2 sec	t_o + 3 sec	t_o + 4 sec	t_o + 5 sec	t_o + 6 sec	t_o + 7 sec	t_o + 8 sec	t_o + 9 sec	t_o + 10 sec	t_o + 11 sec
T-55	13.2	97	20	61	108	167	221	281	---	---	---	---	---
	13.3	146	18	57	102	160	214	272	326	385	436	489	---
	13.5	76	17	56	89	124	154	185	210	237	261	292	318
	14.1	50	20	63	98	133	164	197	225	263	292	323	351
	14.2	166	24	66	106	159	208	265	316	368	412	459	498
	14.3	174	30	75	118	176	232	297	355	416	466	519	559
T-67	5.1	59	22	62	93	---	---	---	---	---	---	---	---
	6.3	62	24	68	103	136	162	188	---	---	---	---	---
	7.1	58	19	59	99	137	173	217	---	---	---	---	---
	7.2	104	21	57	93	132	163	196	224	251	---	---	---
	8.1	66	17	57	92	130	157	196	231	264	291	321	347
	13.1	46	17	48	86	135	180	228	---	---	---	---	---
	13.2	91	11	42	79	128	177	234	---	---	---	---	---
	13.3	138	12	43	79	127	176	231	282	338	385	433	---
	13.5	72	16	53	87	123	154	183	206	232	259	289	317
	14.1	50	37	85	117	148	175	203	225	253	280	311	337
	14.2	163	20	57	93	141	183	231	274	319	359	401	436
	14.3	164	22	57	98	153	203	259	308	361	408	459	499
T-79	5.1	60	17	54	86	---	---	---	---	---	---	---	---
	6.3	62	20	58	92	128	156	185	---	---	---	---	---
	7.1	58	22	62	97	134	168	211	---	---	---	---	---
	7.2	105	17	59	94	130	161	192	220	255	---	---	---
	8.1	66	22	62	98	135	164	198	229	261	286	312	335
	13.1	46	12	34	63	100	138	184	---	---	---	---	---
	13.2	91	15	46	74	118	157	202	---	---	---	---	---
	13.3	138	15	45	76	115	153	198	244	288	331	380	---
	13.5	74	16	46	74	106	135	168	197	228	256	286	313
	14.1	50	33	69	92	119	145	175	201	230	256	284	312
	14.2	163	23	53	85	125	166	215	260	311	355	405	453
	14.3	170	24	52	85	127	169	217	263	314	358	406	445
T-91	5.1	61	15	44	70	---	---	---	---	---	---	---	---
	6.3	63	16	47	75	106	132	157	---	---	---	---	---
	7.1	59	19	50	78	109	138	170	---	---	---	---	---
	7.2	106	18	49	76	107	134	161	184	208	---	---	---
	8.1	67	18	50	77	108	134	163	191	220	246	273	298
	13.1	46	7	20	38	67	100	142	---	---	---	---	---
	13.2	91	6	23	44	77	114	160	---	---	---	---	---
	13.3	137	8	27	47	79	114	158	200	248	290	331	---
	13.5	74	10	34	59	90	120	153	182	214	243	280	312
	14.1	50	21	52	78	107	133	159	181	203	223	247	271
	14.2	166	14	41	70	109	149	194	233	278	318	365	408
	14.3	176	19	47	84	131	174	223	268	315	355	403	440
T-103	5.1	62	18	53	85	---	---	---	---	---	---	---	---
	6.3	65	23	64	97	130	156	182	---	---	---	---	---
	7.1	60	28	71	103	135	166	203	---	---	---	---	---
	7.2	114	24	64	96	129	157	186	210	238	---	---	---
	8.1	68	24	66	97	131	159	192	222	253	281	312	339
	13.1	47	9	32	64	112	157	205	---	---	---	---	---
	13.2	102	5	27	61	113	167	229	---	---	---	---	---
	13.3	142	4	23	54	104	158	219	272	323	364	410	---
	13.5	68	5	25	53	92	131	173	212	254	290	335	377
	14.1	52	10	37	69	112	150	188	220	256	288	321	350
	14.2	173	10	38	73	125	176	235	286	338	383	434	478
	14.3	187	15	46	88	143	194	249	296	344	386	432	470
T-104B	5.1	---	---	---	---	---	---	---	---	---	---	---	---
	6.3	68	12	44	73	102	130	162	---	---	---	---	---
	7.1	64	12	46	77	108	134	157	---	---	---	---	---
	7.2	124	14	48	78	108	132	157	177	199	---	---	---
	8.1	71	14	49	79	108	132	155	173	193	211	234	264
	13.1	48	5	20	41	73	106	146	---	---	---	---	---
	13.2	105	6	26	52	89	127	171	---	---	---	---	---
	13.3	151	6	26	58	96	134	178	218	262	301	345	---
	13.5	67	12	43	72	103	129	153	178	202	225	259	292
	14.1	54	4	17	33	55	77	103	125	150	173	203	233
	14.2	181	3	15	31	55	81	115	149	188	226	268	307
	14.3	197	7	21	41	70	101	139	175	216	254	296	332
T-104C	5.1	67	16	51	78	---	---	---	---	---	---	---	---
	6.3	69	21	61	93	124	150	184	---	---	---	---	---
	7.1	65	18	58	93	128	156	177	---	---	---	---	---
	7.2	125	18	60	94	127	155	185	220	250	---	---	---
	8.1	72	21	66	102	136	162	183	197	209	230	257	287
	13.1	49	8	28	52	83	115	153	---	---	---	---	---
	13.2	106	9	33	59	95	129	170	---	---	---	---	---
	13.3	151	6	25	47	78	110	148	184	224	261	300	---
	13.5	67	24	76	115	148	162	151	149	161	181	201	224
	14.1	55	5	18	34	56	78	104	125	145	156	163	169
	14.2	180	4	16	31	51	70	92	106	118	127	133	137
	14.3	197	7	20	37	62	88	121	152	189	224	259	288

*Thermocouple locations shown in Fig. 7.

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13. ABSTRACT

A test program was conducted to determine the aerodynamic and thermal operating characteristics of a 45-deg-slant, segmented wall, magnetohydrodynamic generator channel under no-power conditions. The generator channel was 30.3 in. long with an inside diameter of 2.0 in. at the inlet that diverged to 4.9 in. at the channel exit. The plasma was provided by a liquid-oxygen/JP-4 combustor with a nozzle exit Mach number of 1.76. The propellants were seeded with potassium hydroxide (KOH) dissolved in ethyl alcohol to produce a high ion concentration in the exhaust stream. Combustor operating conditions were nominally: chamber pressure, 250 to 300 psia; oxidizer-to-fuel ratio, 1.9 to 2.8; and KOH concentration, from 0 to 1.7 percent of total propellant weight flow. Firing durations ranged from 2.6 to 10.9 sec. Tabulations of combustor performance data and of the generator channel thermal and pressure data are presented.

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